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Plasma Design of the EQ-10 EUV Source :

Helping Make EUVL Reality

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Outline

- The Electrodeless Z-Pinch™
- What determines plasma geometry
- Today's EUV mask metrology tool source requirements
- Improvements to Cost of Ownership
- Support for EUV Photoresist Development
- Summary

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Electrodeless Z-Pinch™ EUV Source

- Our group had decades of experience with inductive plasmas
  - Controlled fusion program (U. Wisconsin, MIT Plasma Fusion Center)
  - Industrial applications (Atomic Fluorine and other radicals)
- Advances in magnetic materials –(fast switching cores) and power electronics enabled a new device to be designed.
- Energetiq was founded to develop and commercialize EUV sources.

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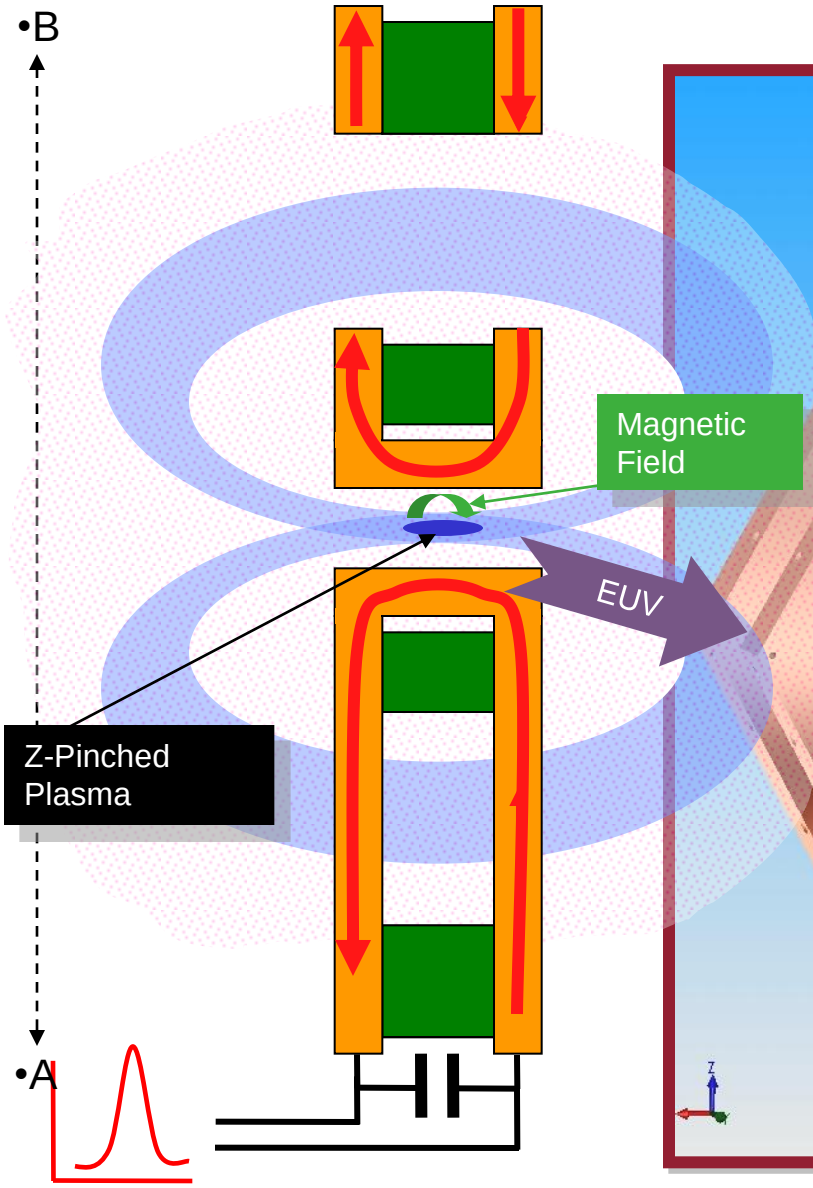
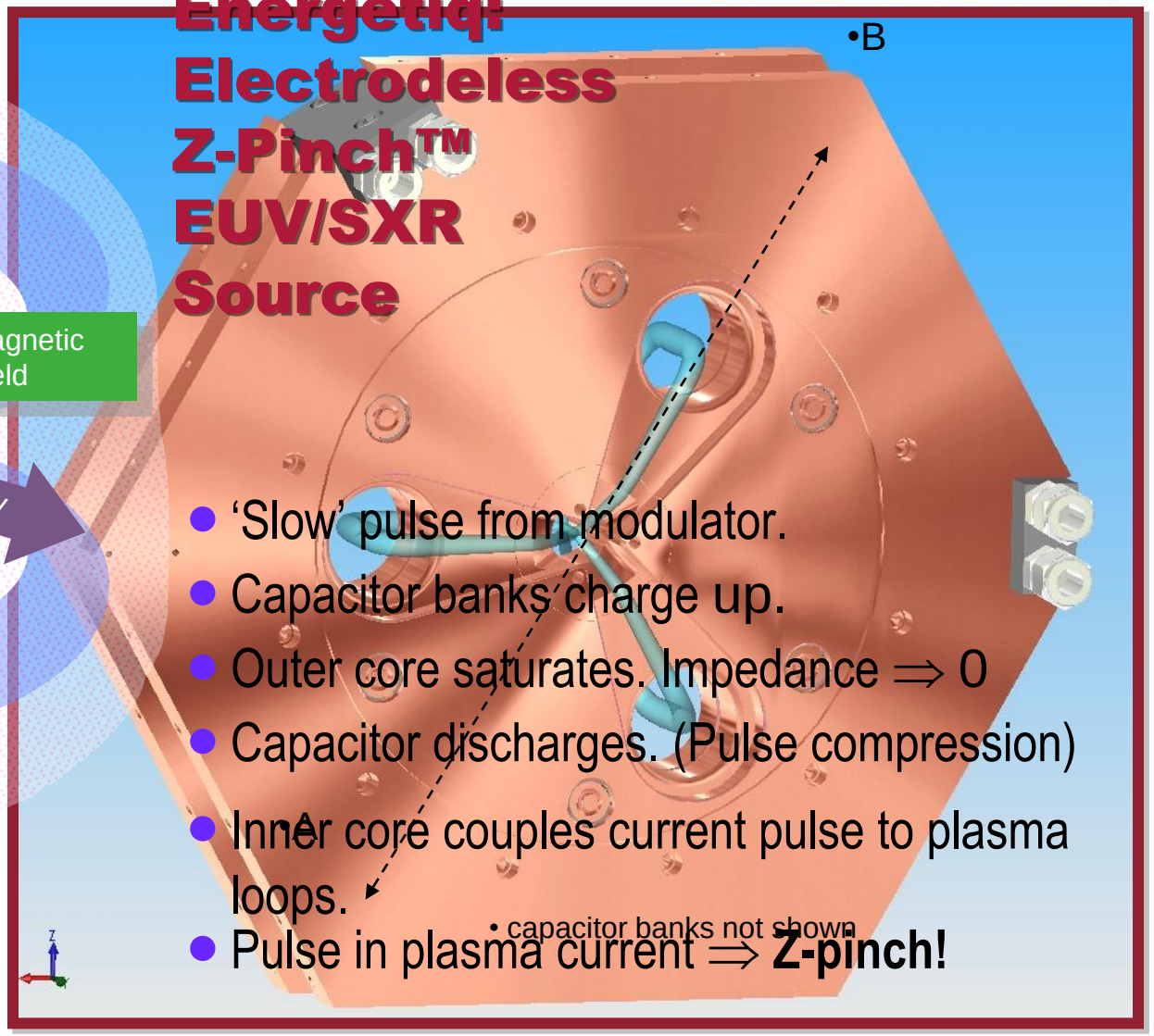
Energetiq: Electrodeless Z-Pinch™ EUV/SXR Source





- 'Slow' pulse from modulator.
- Capacitor banks charge up.
- Outer core saturates. Impedance ⇒ 0
- Capacitor discharges. (Pulse compression)
- Inner core couples current pulse to plasma loops.
- Pulse in plasma current ⇒ **Z-pinch!**

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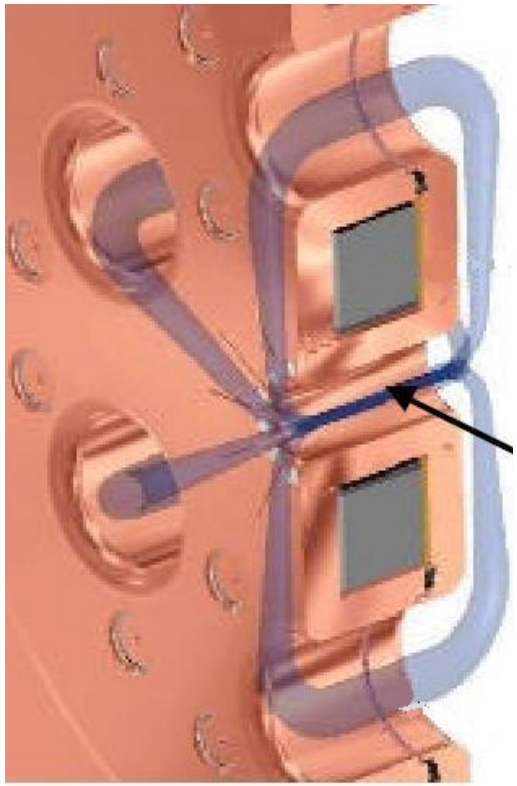
How does the EQ-10 Source control plasma geometry?

- Standard Z-pinch has electrodes –
- Forces plasma to have a specific maximum length – can't be longer than distance between electrodes, because current flows only there
- A small (short) EUV emission region simplifies optics design, saves wasted light/power…
- Electrode-less pinch has current flow over long region. How to control plasma length?

To control plasma length, control plasma radius…



- Total voltage around plasma loop determined by magnetic flux in core. Current is constant around length of loop, so…
- Electric field distribution along plasma loop determined by plasma impedance. Current is ramping, so inductance/length is key.
- Inductance/unit length dL/dl ~ log(1/r) - r-> zero, dL/dl approaches infinity.
- Most of the applied voltage appears across the narrowest plasma cross-section. Nearly all the pulse energy is dissipated there.
- To control plasma length, control the radius.

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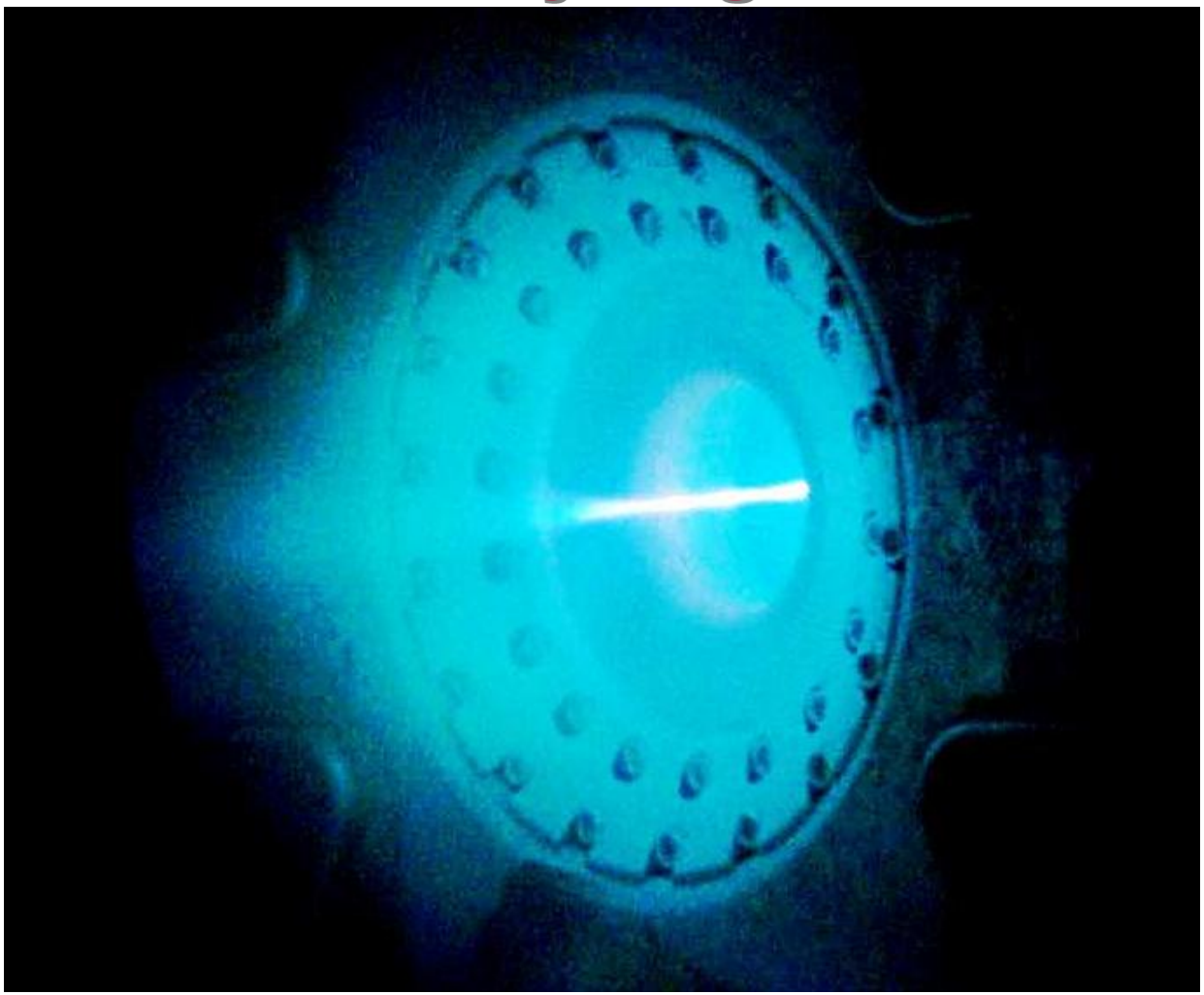
First experiments had very large “bore”

- No attempt to control plasma length –
- ~ 8 cm long plasma!



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Bore Materials and Lifetime

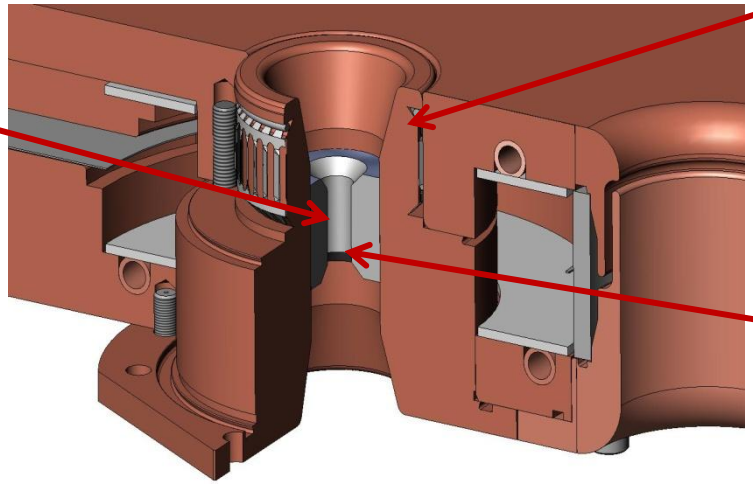
- Copper (erodes quickly, sputters, develops “wormholes”)
- Boron Nitride (poor thermal conductivity; runs white-hot, EUV power low)
- Tungsten (Sputters/develops “wormholes”, produces debris)
- Graphite (Runs very hot, produces debris)
- Silicon Carbide (Only material to survive > 1.e9 pulses)
- Tin (melted in ~ 5 seconds)
- SiC with Titanium liner (very similar to SiC)

These materials were tested in various shapes and diameters – at least 30 combinations

SiC gave least debris and longest life.

EQ-10 Consumable - Bore

- The bore is the part where the EUV Pinch occurs



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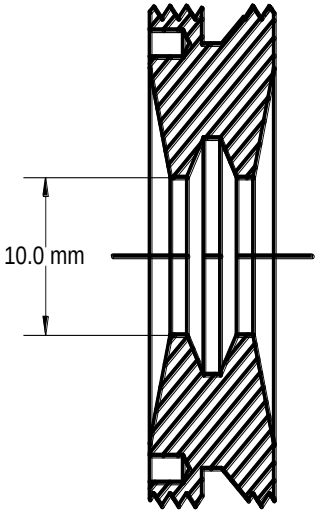
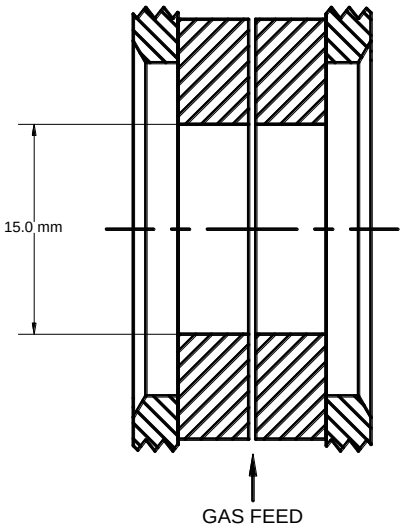
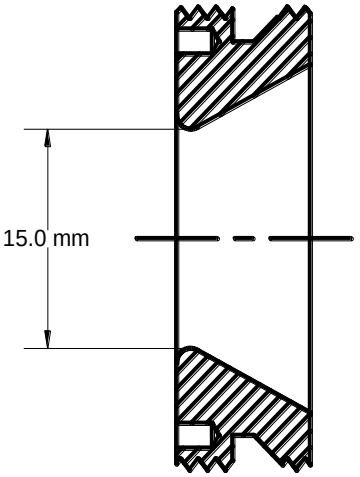
A program to investigate plasma size, lifetime issues…

- Various bore geometries and materials tested – examples…







Silicon Carbide, specific geometry

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Material	Length	Diam	Geometry	Pwr(2pi)	Etendue	Fwhm l	Fwhm d
POCO Graphite	0.96	15	offset	31.36	6.9005	7.3859	0.836
POCO Graphite	0.96	10	recurve	4.95		3.1	2.3
Oriented Graphite	1.5	10	washer	26.25	6.6421	7.4551	0.7994
Oriented Graphite	1.5	15	washer	25.67	7.714	5.5958	1.187
Oriented Graphite	4.5	10	3 washers	25.91	2.543	3.867	0.5815
Oriented Graphite	3	15	washer	33.08	5.3696	6.6506	0.724
Silicon Carbide	5	15	washer	32.72	3.6709	4.8996	0.6661
Silicon Carbide	3	15	2 washers	32.15	5.5233	5.2937	0.9145
Silicon Carbide	3	15	2 washers	10.02	5.7322	5.4921	0.917
Silicon Carbide	3	15	2 washers	9.74	7.2776	6.251	1.0242

Learning from prototype → commercial metrology source… key points

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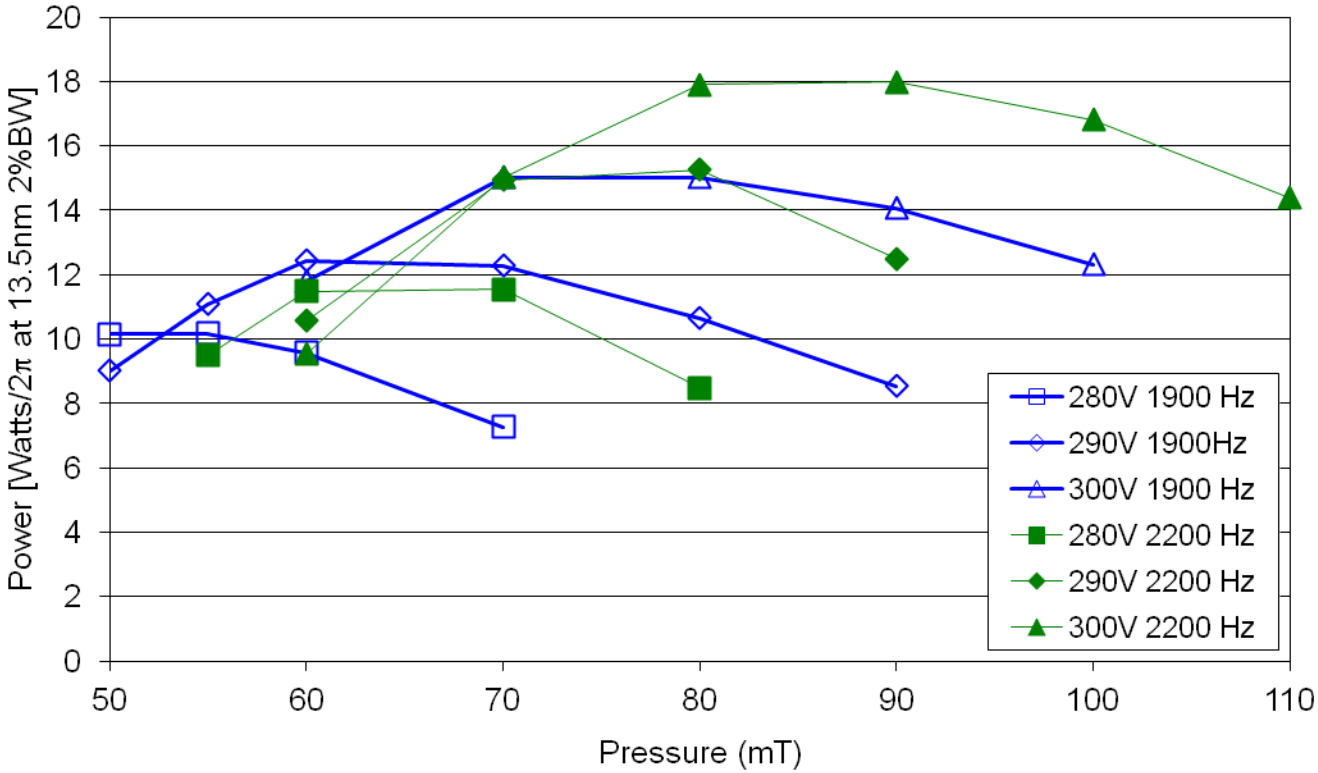
- Plasma size drives optical design process –
  - Pick a geometry and stick with it…
- A 25 eV Xenon plasma is a fierce environment for materials
  - Lifetime of plasma-facing components determine maintenance interval.
  - Resistance to sputtering is key.
- For some metrology, smaller etendue is acceptable.
  - Long plasmas, small collection angles easier to manage
    - More power and brightness from source
    - Simpler optics in instrument.
    - Smaller foils, mitigation structures
- Plasma can be manipulated to match optics design by design of bore insert and operating conditions

Xenon source performance: EUV power

- Power in Watts, into 2π steradians , within 2% BW of 13.5 nm :



- Parameters: input voltage and pulse rate. Input power here ~ 4 – 5 kW
- Input pulse energy increases with input DC voltage

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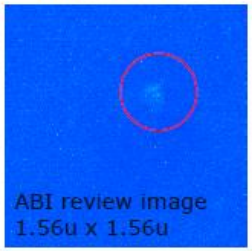
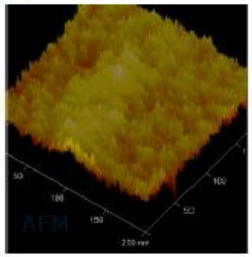
EUV Mask Metrology Needs

ABI new capability enables blank defect reduction and mitigation

Defect 68 – bump

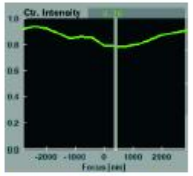




Height: 1.0 nm
FWHM: 36.8 nm

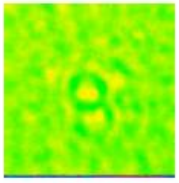
Figure 2: Actinic Blank Inspection Tool at the Lasertec facility in Shin-Yokohama, Japan

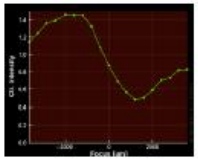
Source: Lasertec paper 2013 SPIE



Annular (0.33NA, sigma=0.2-0.9)

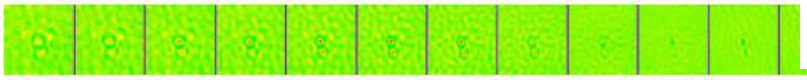
dz=0.4μm,





Coherent (sigma=0.1)

dz=0.4μm,

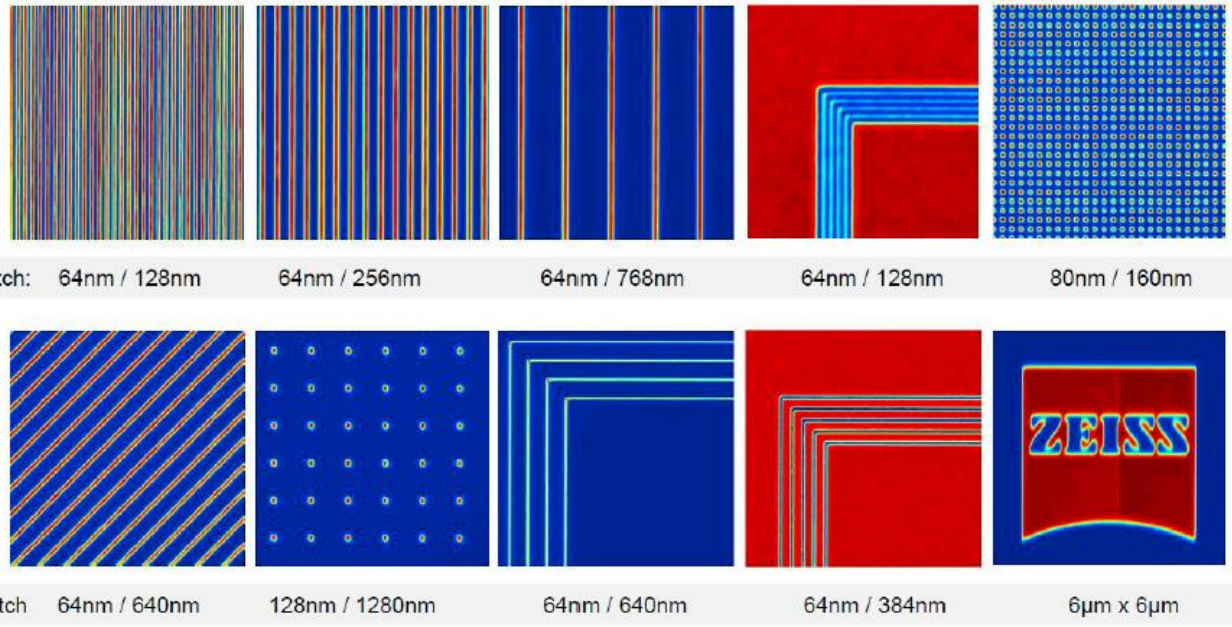


The tool performs better than expected

15 Lasertec

Guojing Zhang et al. (Intel) BACUS 2014, Monterey, California, USA, 9/18/2014

AIMS™ EUV images from EMI prototype system



Source: Courtesy of Zeiss

- Adequate imaging performance at the first light demonstrated for target application at 7nm logic node
- System integration and operation reliability will be tested for EUV mask manufacturing

Guojing Zhang et al. (Intel) BACUS 2014, Monterey, California, USA, 9/18/2014

International Workshop on EUV and Soft X-Ray Sources, 4 November 2014, Mark Phillips (Intel)

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No change from 2013 Workshop

Challenge to actinic metrology source community

Based on input from metrology tool suppliers and Intel metrology experts:

- Existing sources do not meet brightness, homogeneity, stability, and COO requirements
  - Requirements are feasible, but already late to need
  - Requires focused development activity and funding
- Requirements are specific to each tool design, and are proprietary
  - Source is an integrated part of tool design
  - Correct model is funding through metrology tool suppliers

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Metrology Source Challenges

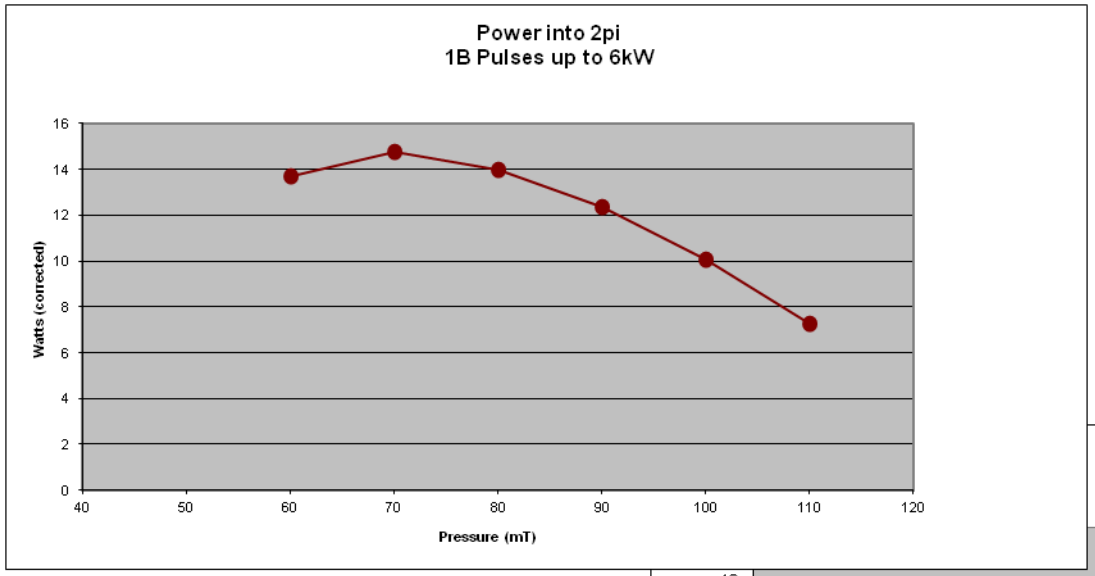
- Brightness is ok for AIMs and ABI
- What's critical for today's tools?

- COO ---------- Downtime
  ---------- Cost

- Consistent Output ----------Repeatable Results

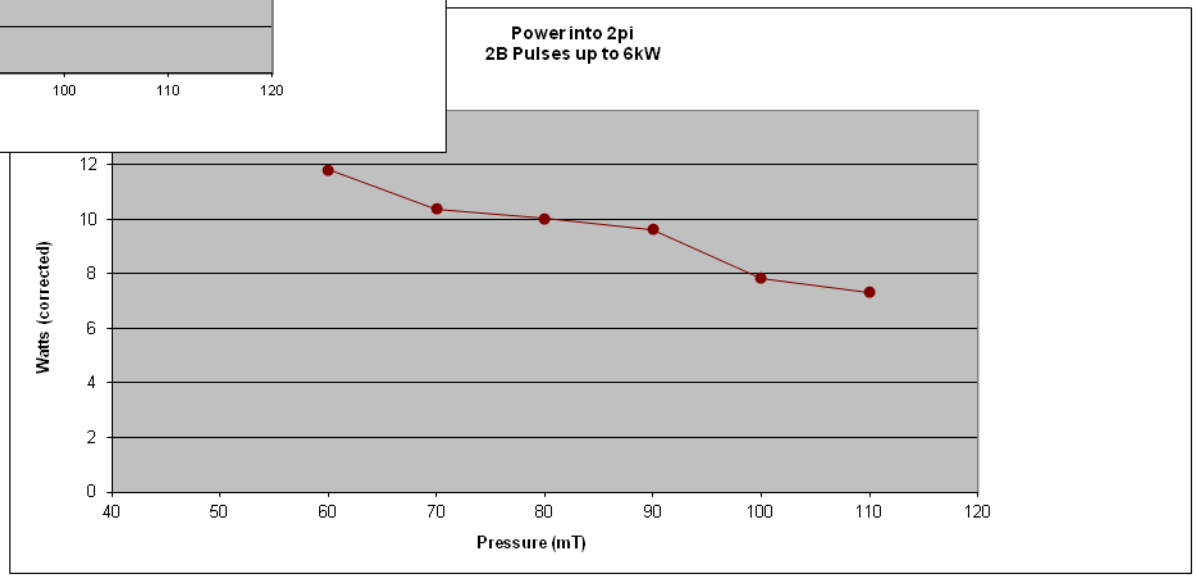
- EQ-10 only consumable is the bore

Energetiq Source Lifetime of Bore



Goal

- 1 week 24/7 operation
- Minimal change in output power
- Continued stability



COO Improvement

	Conditioning	Operation	Time to change	Availability
2013	24 hours	1 Billion Pulses (114 hours)	4 hours	80%
2014	Preconditioned*	168 hours	4 hours	97%

•Lifetime improvements are realized by operation of the source at optimal conditions over the lifetime of the bore to enable consistent output and improve availability of the source to >95%

* can be done at Energetiq prior to shipment

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EUV Photoresist Development Support

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Photoresist Sensitivity Measurements

- Development of new photoresist is becoming critical for HVM of EUV
- Sensitivity of the photoresist is one important criteria in evaluating the success
- Stand-alone systems for these measurements will reduce time to market for these photoresists

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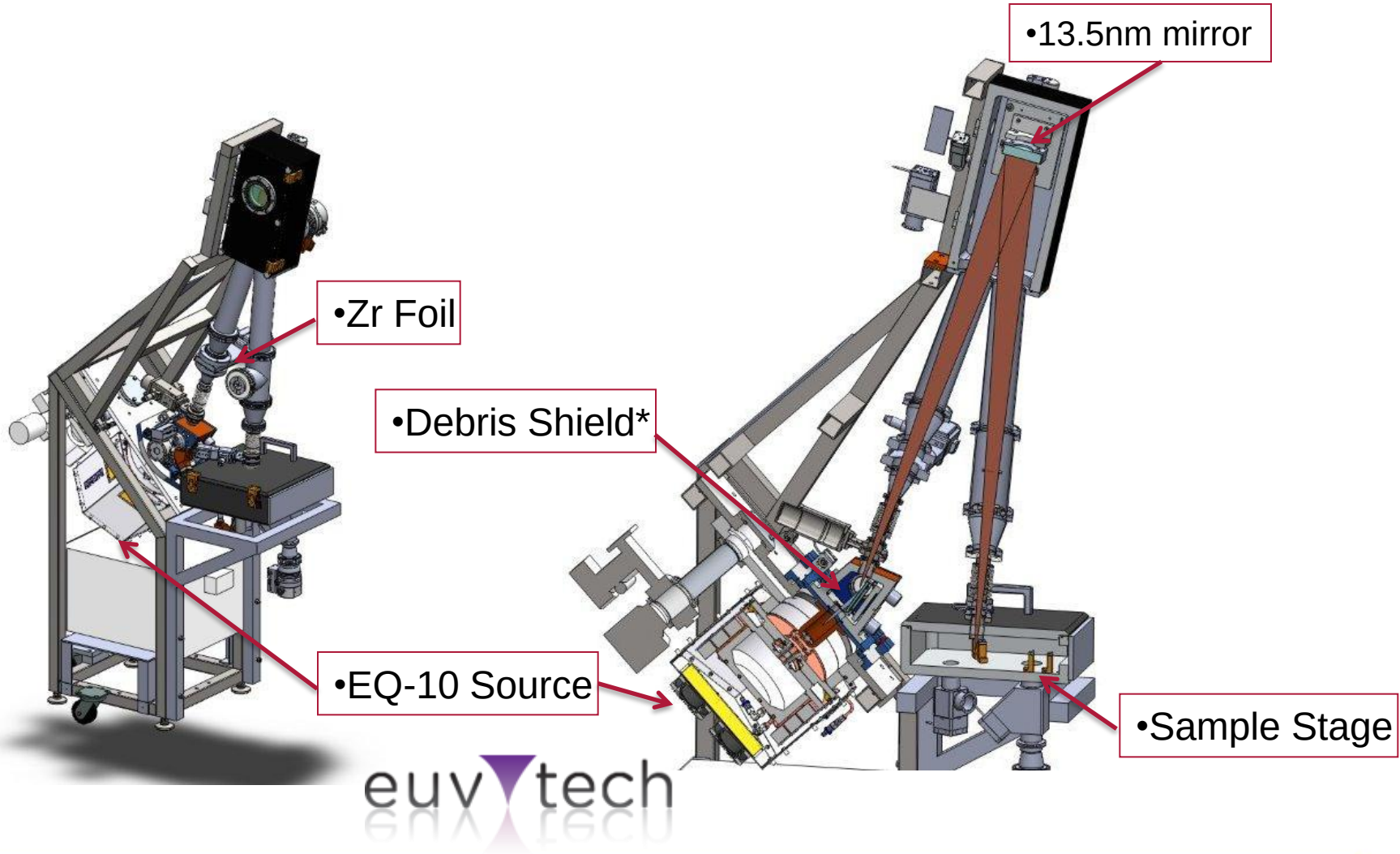
EUV Exposure/Resist Sensitivity Tool



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Estimated Power at Sample - Example

Source Brightness W/mm2.sr	4
Solid half angle degrees	~1.5
Solid angle sr	0.002
Source diameter	0.5
Source area mm2	0.19625
Power from source in solid angle mW	1.57
Reflectivity of mirror	0.65
Transmission of 150nm foil	0.5
Xe transmission	0.9
Grazing incidence mirror reflectivity	0.9
Power at substrate in +/- 1% band mW	0.459225
Power in 3.5% band (estimate) mW	**0.75772125**

EUV Exposure

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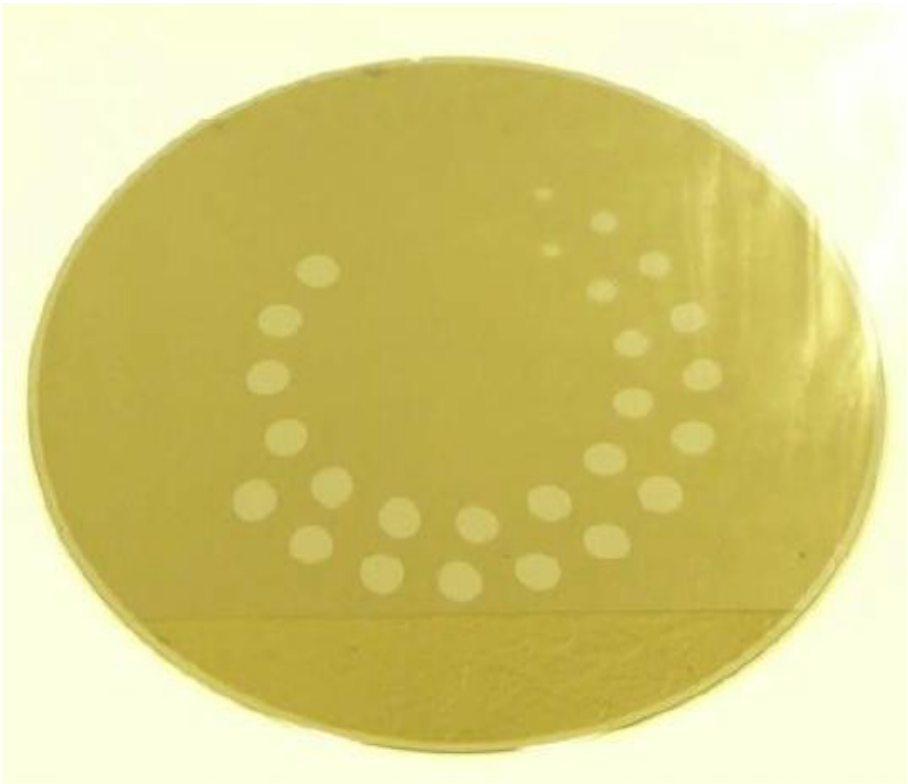
•DTC Sweep

•DTC Pulse



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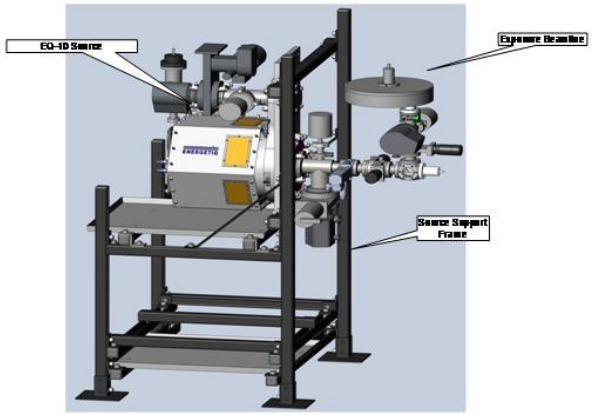
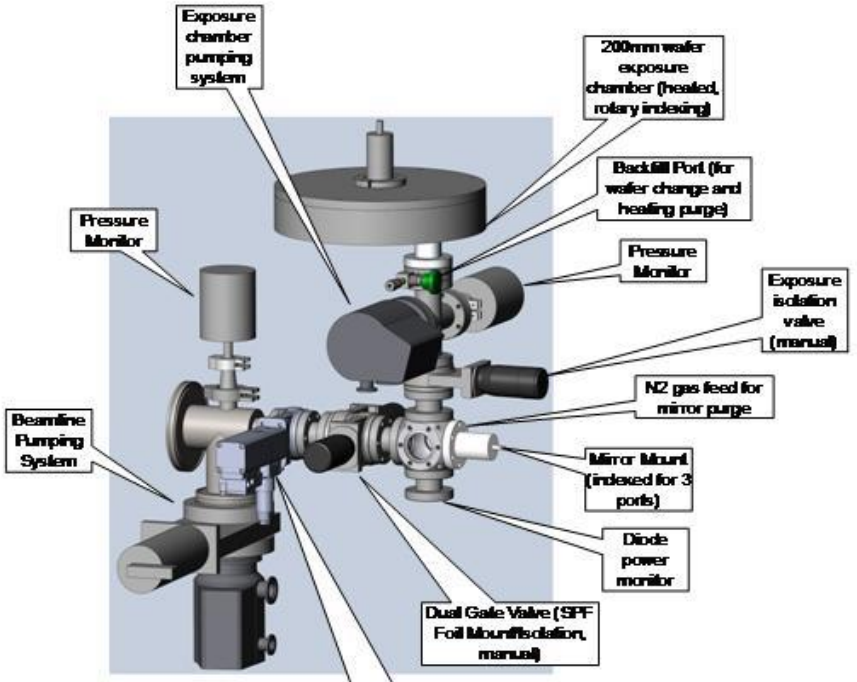
Open Frame Exposure System





LTJ リソテックジャパン株式会社 Litho Tech Japan

The construction of the system

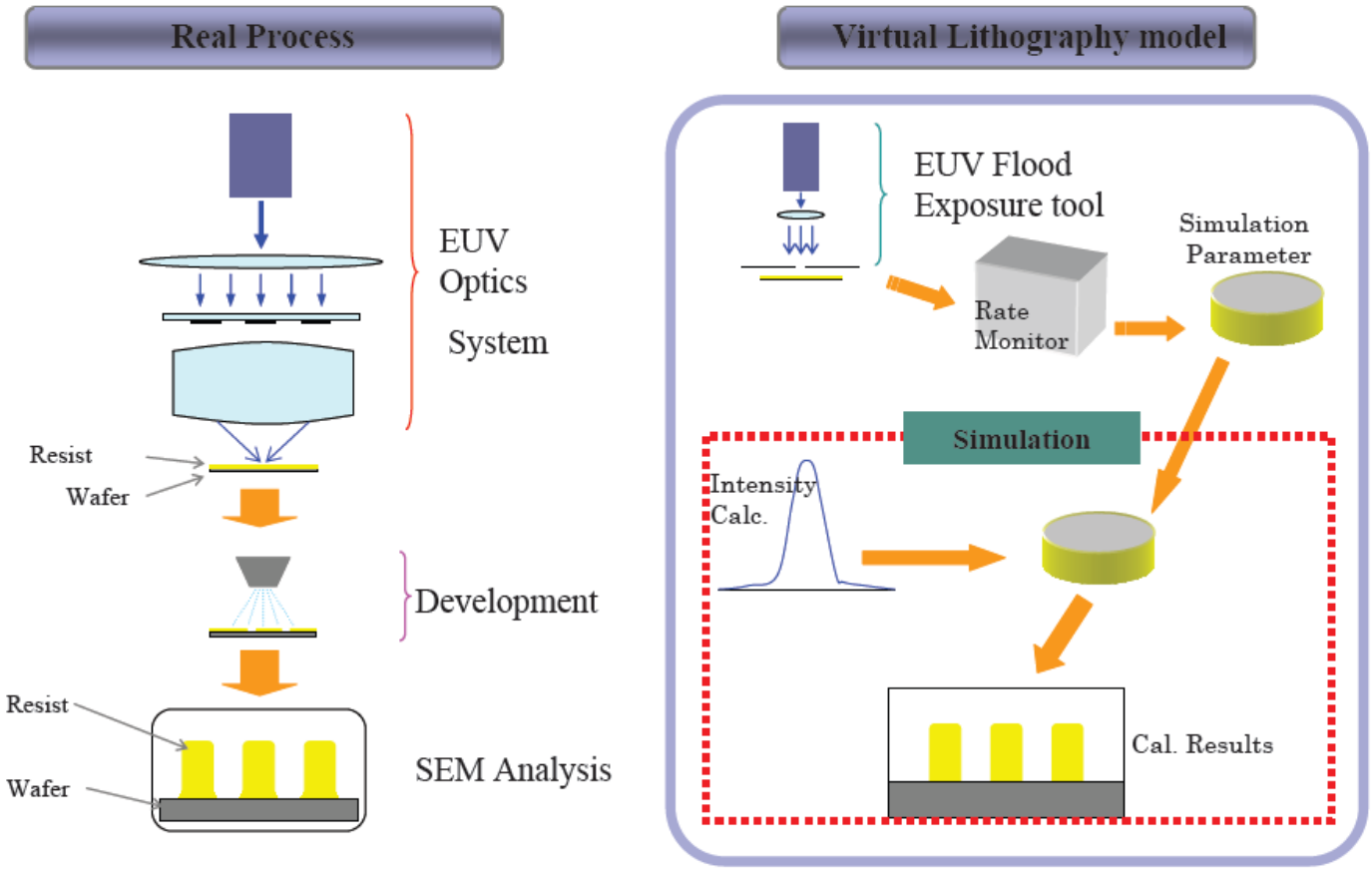
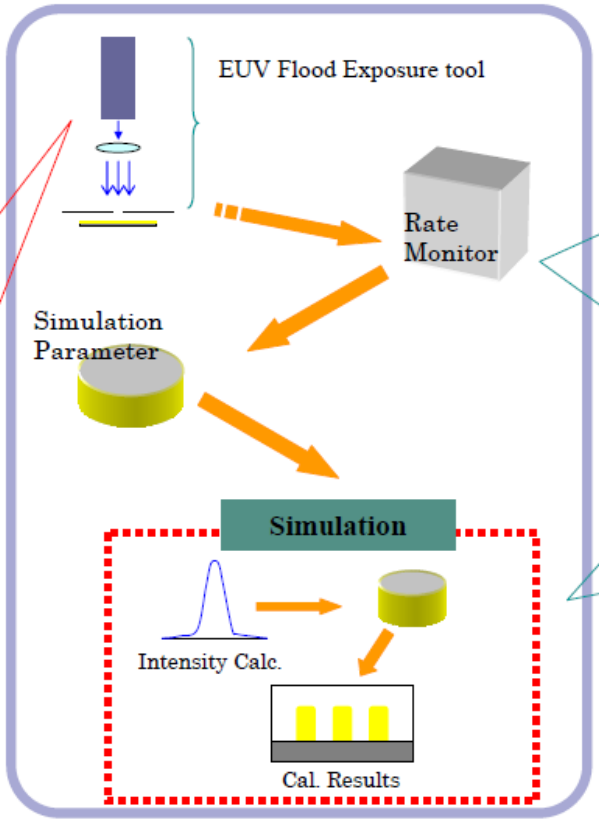


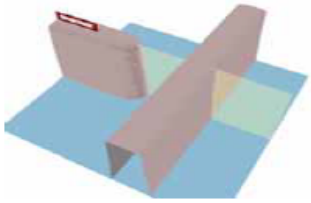
Photo-chemical Analysis System for EUV Lithography

The virtual lithography evaluation system (VLES)

EUVES-7000



RDA-800_EUV



Prolith
KLA FINLE

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The Exposure Sample

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Closing Remarks

- Control of the design of the bore can support optical designs as needed.
  - Large radius, short plasma
  - Small radius, long plasma etc.
- The Energetiq EQ-10 EUV source is a reliable and stable source of EUV photons that offers >95% availability
- Simple systems can be used for resist dose measurements

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Acknowledgements

- The team at Energetiq…
- Our valued customers…
  - LTJ
  - EUV Technology
- Our excellent partners and collaborators…

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Thank you!